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Yao

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[45] Date of Patent: Aug. 18, 1998

[54] **LADDER-STRUCTURED PHOTONIC VARIABLE DELAY DEVICE**

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[21] Appl. No.: **835,352**

[22] Filed: **Apr. 7, 1997**

Related U.S. Application Data

[62] Division of Ser. No. 564,920, Nov. 30, 1995.

[51] **Int. Cl.**[6] **G02F 1/03**

[52] **U.S. Cl.** **359/256**; 359/245; 359/250; 359/259; 359/316

[58] **Field of Search** 359/250, 245, 359/256, 257, 259, 301, 316, 320, 322, 324, 39; 349/96

[56] **References Cited**

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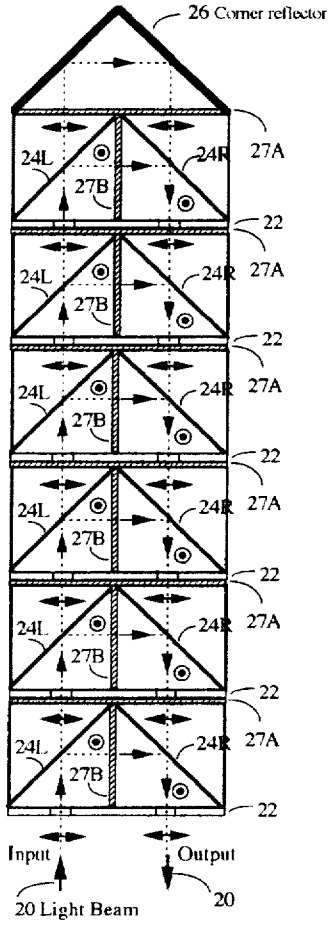
Primary Examiner—Loha Ben

[57] **ABSTRACT**

An ladder-structured variable delay device for providing variable true time delay to multiple optical beams simultaneously. The device comprises multiple basic units stacked on top of each other resembling a ladder. Each basic unit comprises a polarization sensitive corner reflector formed by two polarization beamsplitters and a polarization rotator array placed parallel to the hypotenuse of the corner reflector. Controlling an array element of the polarization rotator array causes an optical beam passing through the array element to either go up to a basic unit above it or reflect back towards output. The beams going higher on the "ladder" experience longer optical path delay. Finally, the ladder-structured variable device can be cascaded with another multi-channel delay device to form a new device which combines the advantages of the two individual devices. This programmable optic device has the properties of high packing density, low loss, easy fabrication, and virtually infinite bandwidth. In addition, the delay is reversible so that the same delay device can be used for both antenna transmitting and receiving.

20 Claims, 11 Drawing Sheets



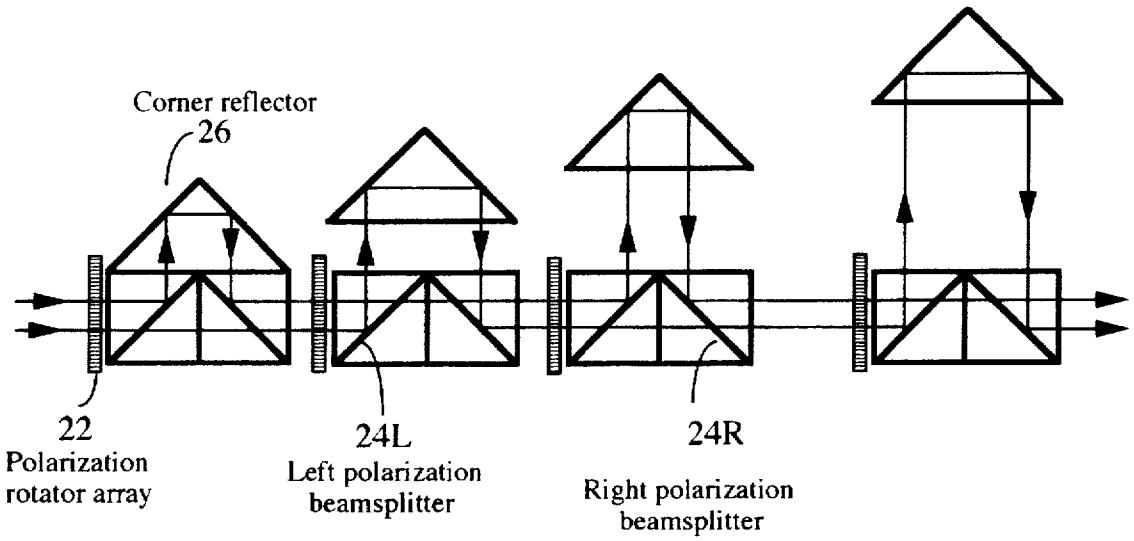


Fig. 1A (Prior Art)

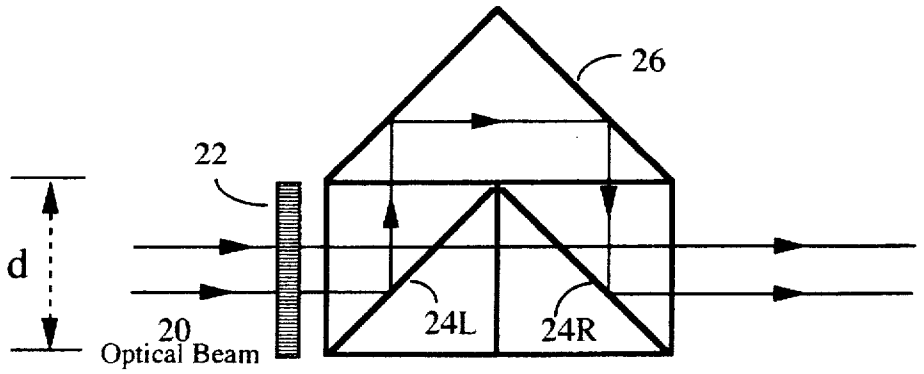


Fig. 1B (Prior Art)

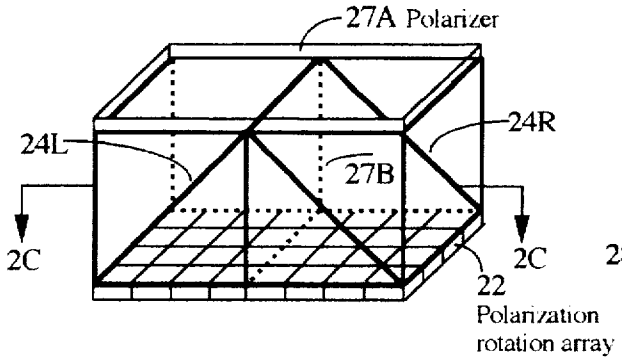


Fig. 2A

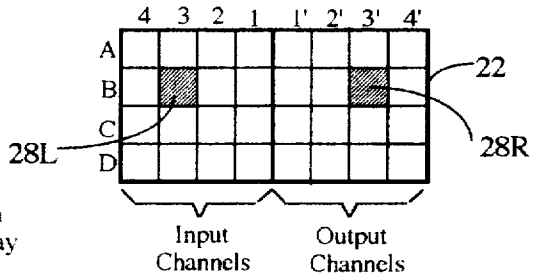


Fig. 2B

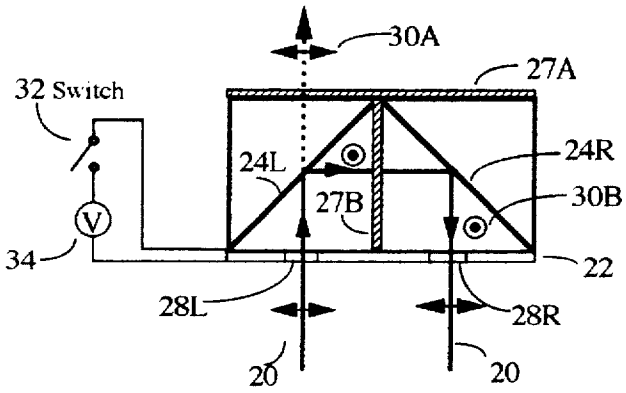


Fig. 2C

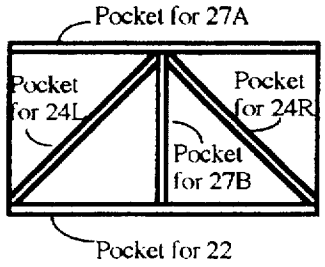


Fig. 2D

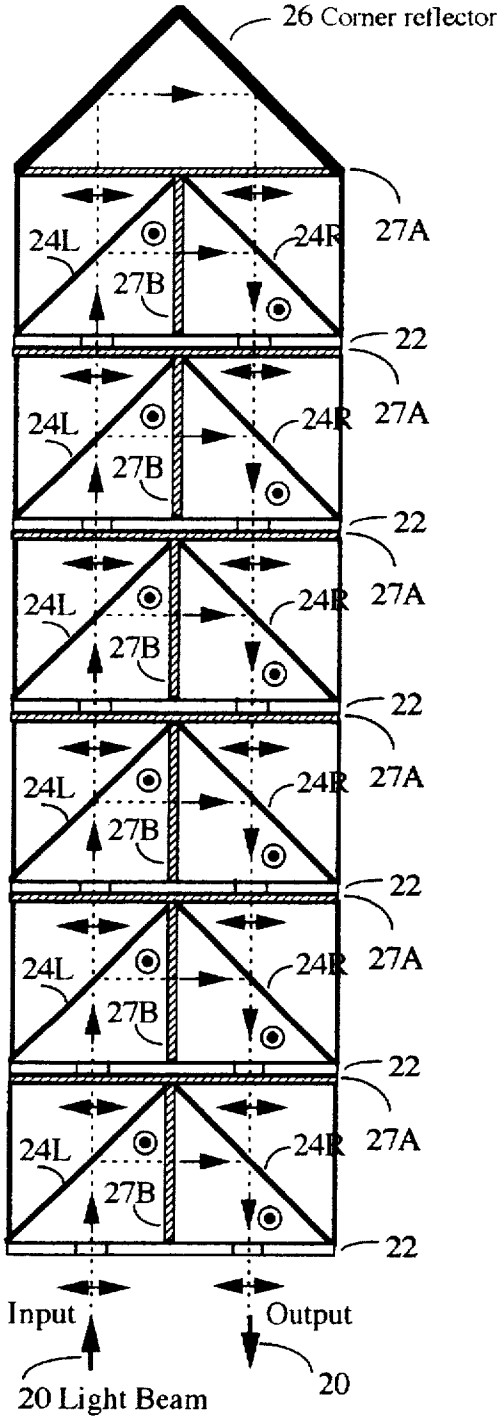

26 Corner reflector
24L
24R
27A
27B
22
Input
Output
20 Light Beam
20

Fig. 3A

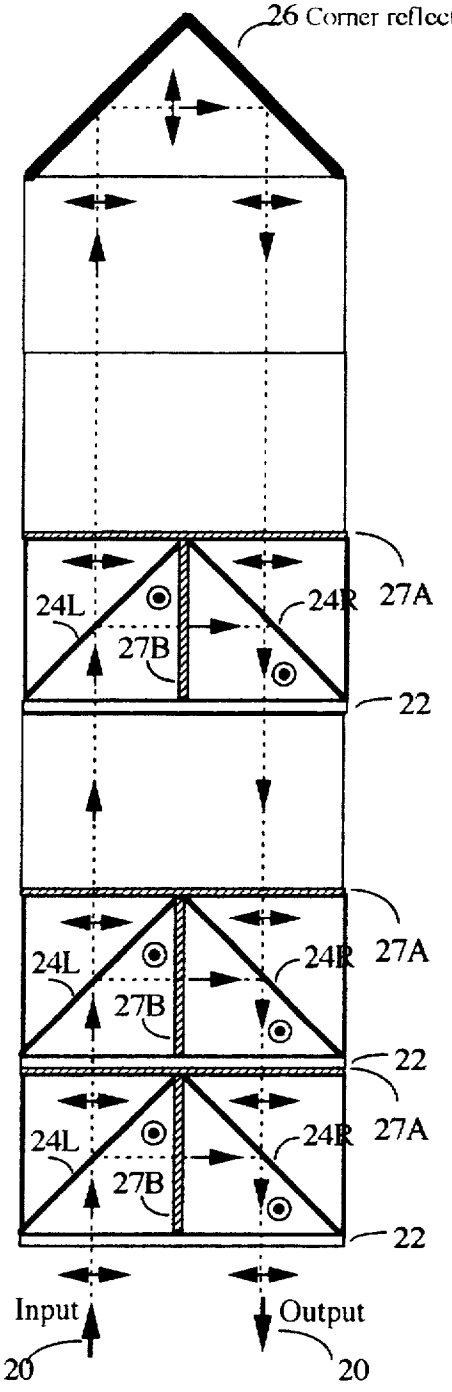

26 Corner reflector
24L
24R
27A
27B
22
Input
Output
20
20

Fig. 3B

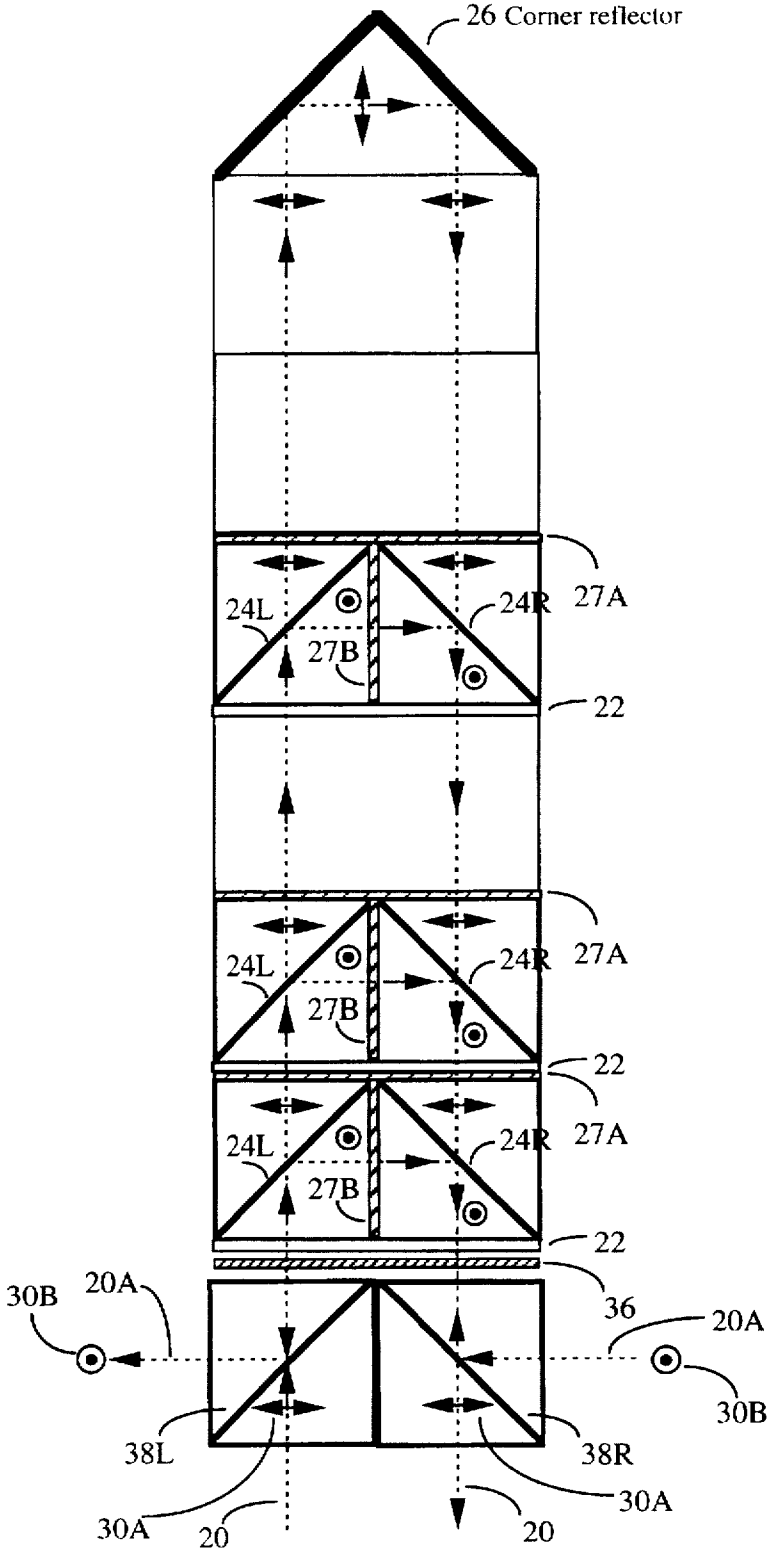

26 Corner reflector
24L
24R
27A
27B
22
24L
24R
27A
27B
22
24L
24R
27A
27B
22
36
30B
20A
20A
30B
38L
38R
30A
30A
20
20

Fig. 3C

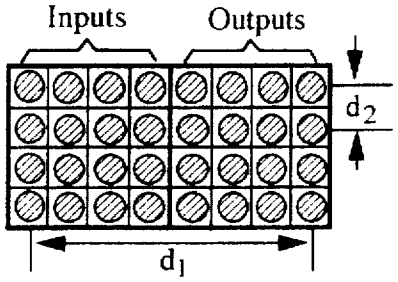


Fig. 4A

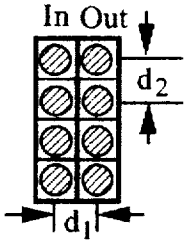


Fig. 4B

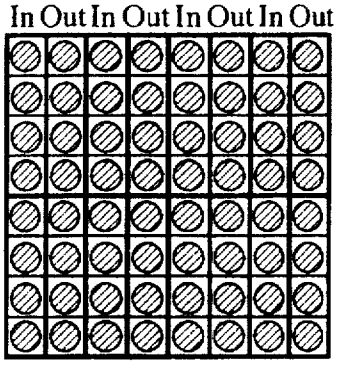


Fig. 4C

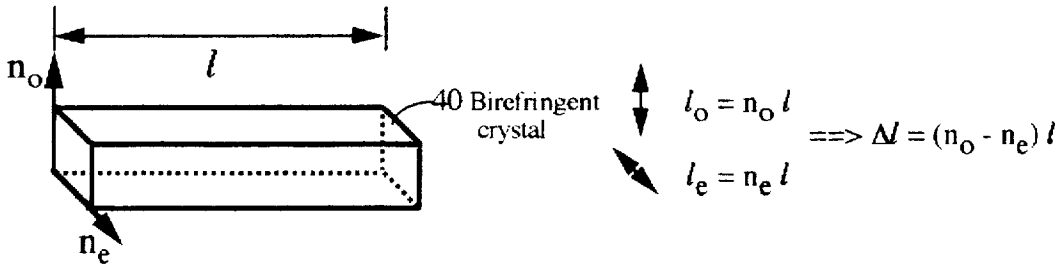


Fig. 5A

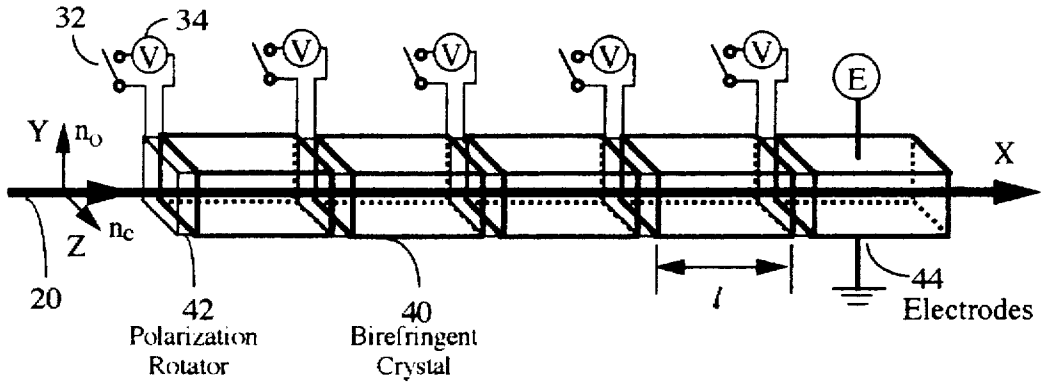


Fig. 5B

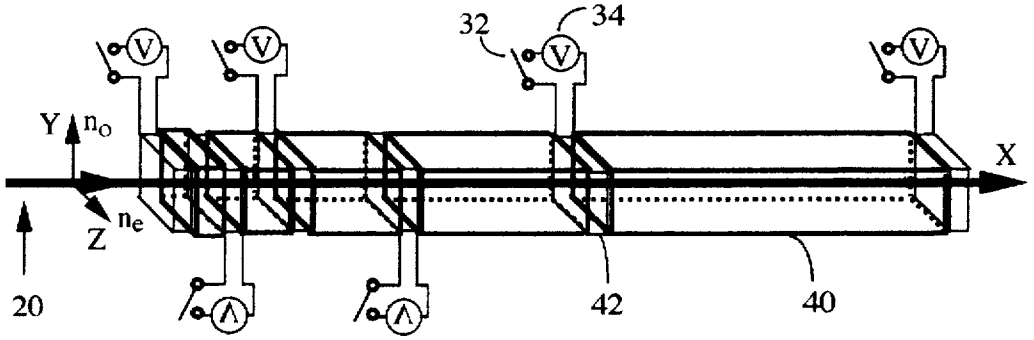


Fig. 5C

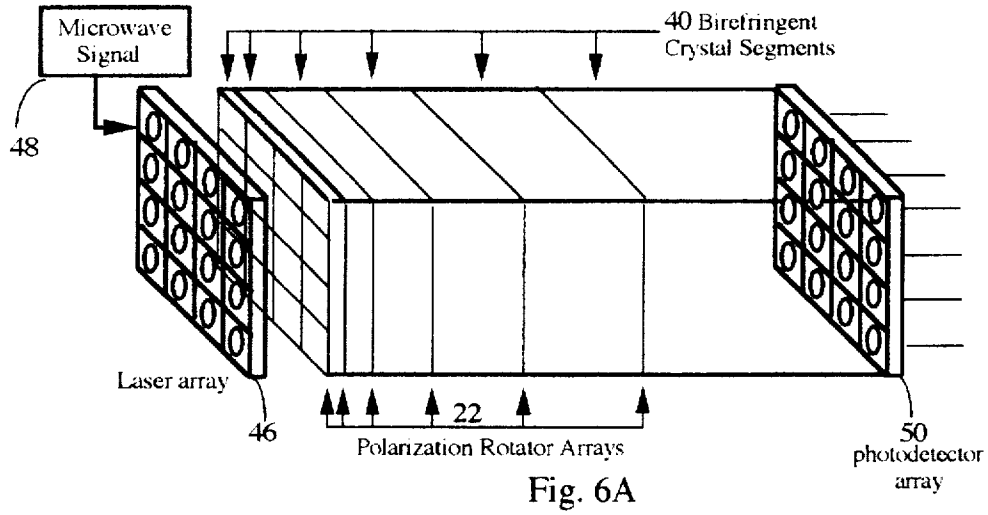


Fig. 6A

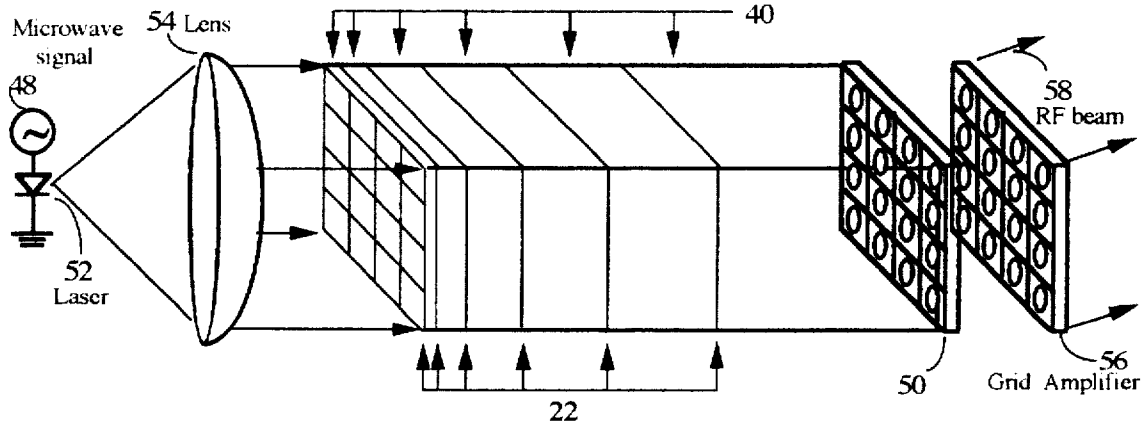


Fig. 6B

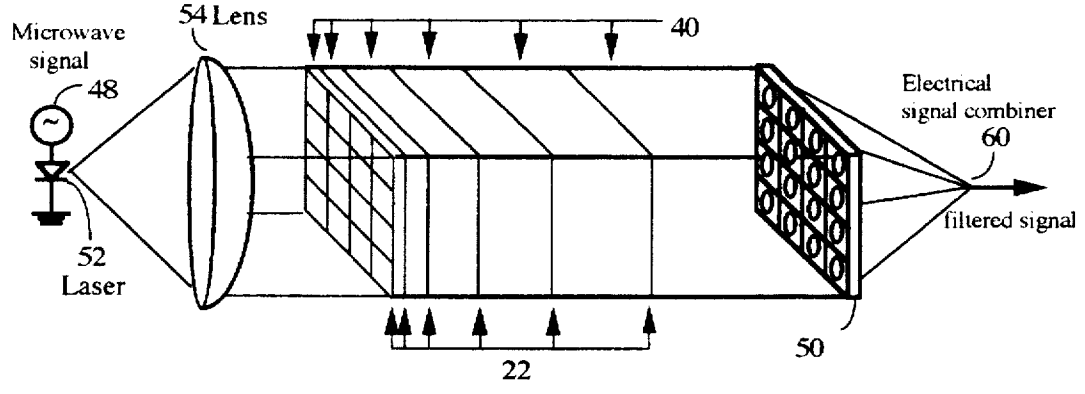


Fig. 6C

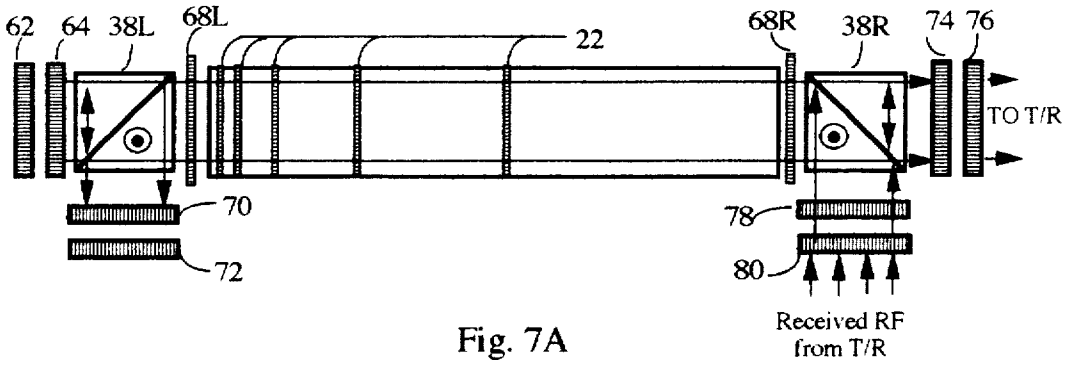

62
64
38L
68L
22
68R
38R
74
76
TO T/R
70
72
78
80
Received RF
from T/R

Fig. 7A

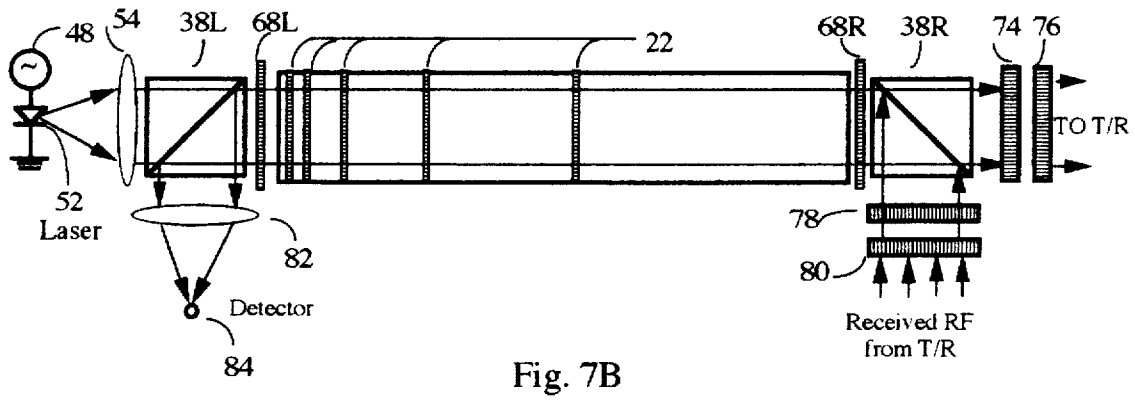

48
54
38L
68L
22
68R
38R
74
76
TO T/R
52
Laser
82
Detector
84
78
80
Received RF
from T/R

Fig. 7B

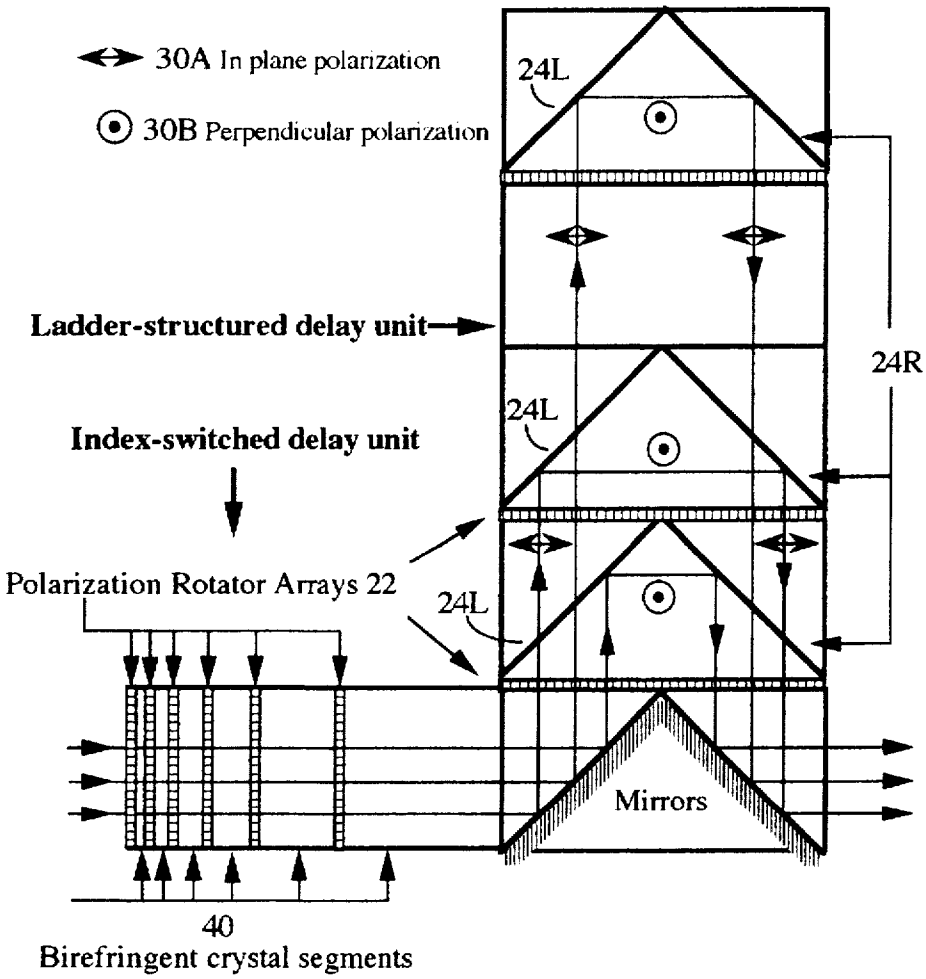

30A In plane polarization
30B Perpendicular polarization
24L
Ladder-structured delay unit
24R
24L
Index-switched delay unit
Polarization Rotator Arrays 22
24L
Mirrors
40
Birefringent crystal segments

Fig. 8

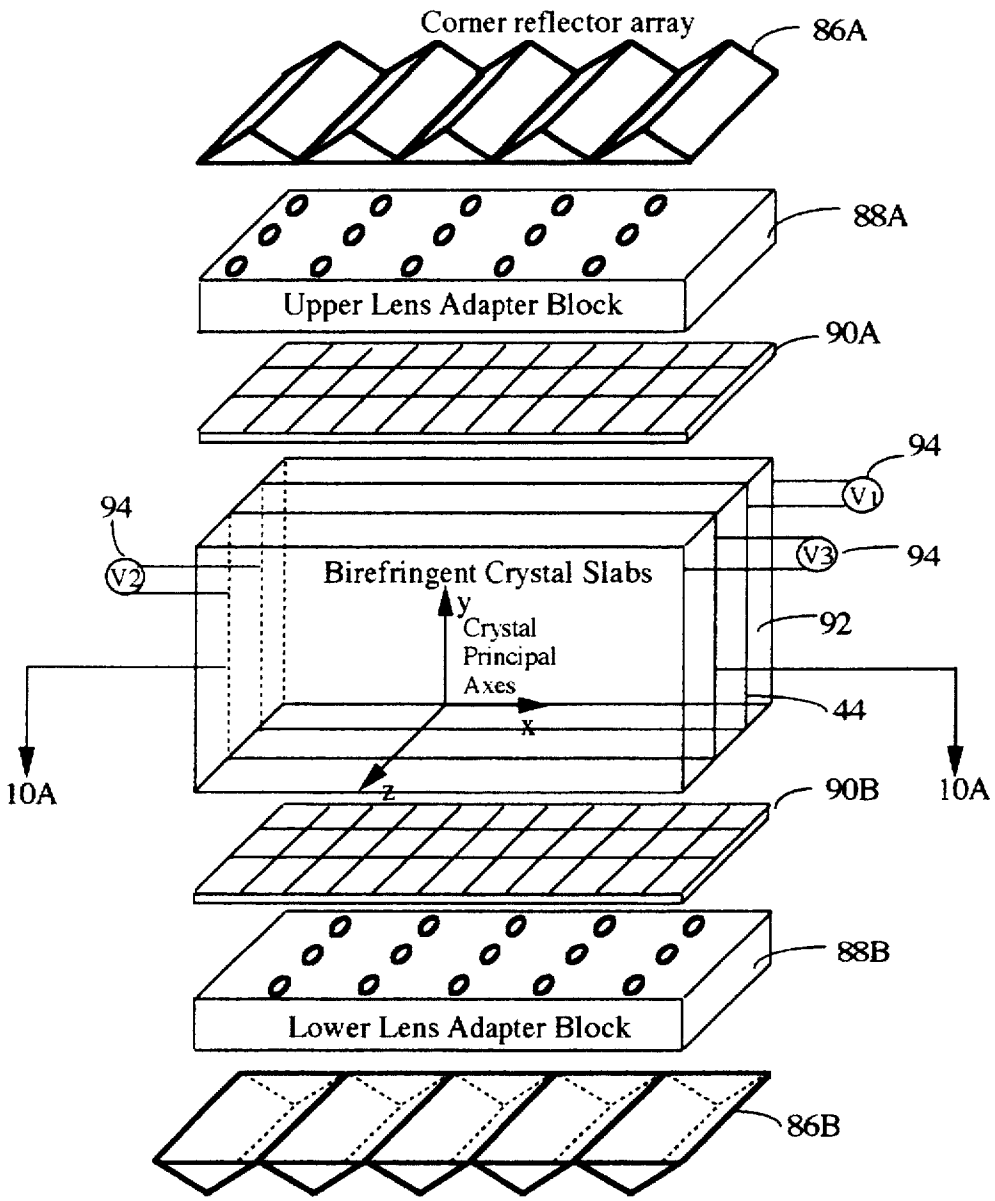

Corner reflector array
86A
88A
Upper Lens Adapter Block
90A
94
V1
94
V2
V3
94
Birefringent Crystal Slabs
y
Crystal
Principal
Axes
92
x
44
z
10A
10A
90B
88B
Lower Lens Adapter Block
86B

Fig. 9

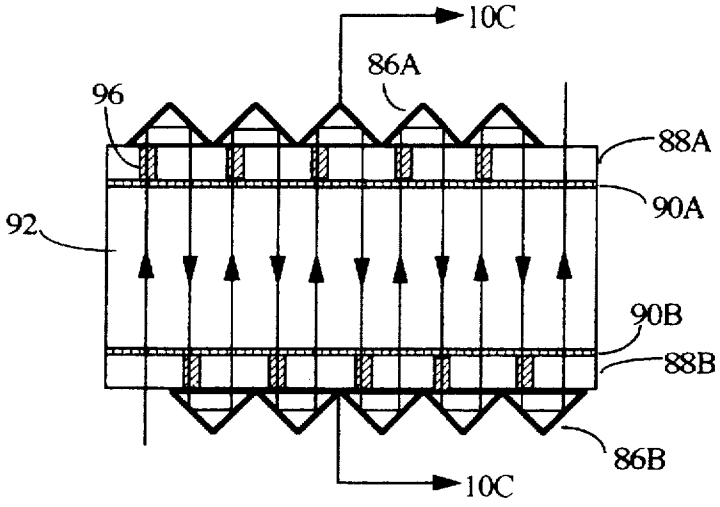


Fig. 10A

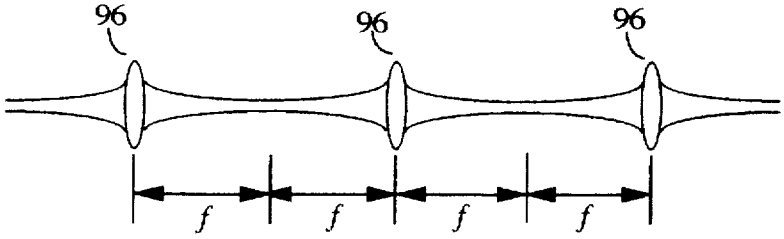


Fig. 10B

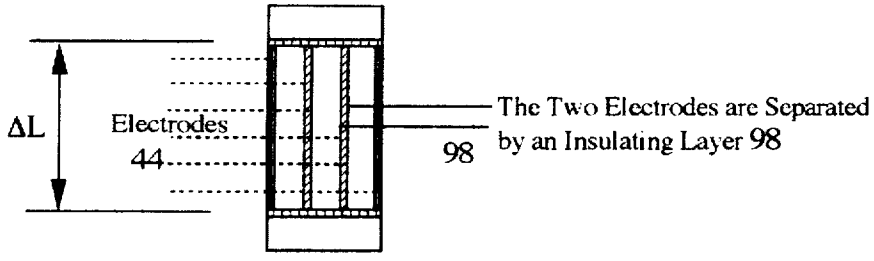


Fig. 10C

LADDER-STRUCTURED PHOTONIC VARIABLE DELAY DEVICE

This is a division of Ser. No. 08/564,920, filed Nov. 30, 1995.

FIELD OF THE INVENTION

This invention pertains generally to the precision optical path length control, specifically to a photonic variable true time delay device for steering phased array radar, for constructing a transversal filter, and for controlling the optical path in optical interferometry. This invention was made with Government support under a Contract awarded by NASA, and is subject to the provisions of Public Law 96-517 A (35 U.S.C 202) in which the inventor is granted right to retain title. The government has certain rights in this invention.

BACKGROUND AND SUMMARY OF THE INVENTION

Phased array antennas have the important ability of beam steering without mechanical actuators. This feature is highly desirable for applications such as spacecraft, air craft, and mobile platforms where size and mass are restricted. The direction of a microwave (or millimeter wave) beam radiated from a phased array antenna is generally controlled by the relative phase distribution of microwave signals emitted by regularly spaced radiating elements. For a phased array of a wide instantaneous bandwidth, adjusting only the relative phase is not sufficient and so a relative time delay adjustment of the radiating elements must be introduced to avoid the beam pointing error known as squint, which results from the modification of the antenna phase pattern with changing frequency.

Conventional electronic beam forming systems for generating and delivering the requisite time delay and phase information are generally bulky, lossy, inefficient, and of narrow bandwidth. On the other hand, photonic beam forming offers the advantage of high packing density, wide signal bandwidth, light weight, immunity to electromagnetic interference, and remoting capability via optical fiber. Consequently, it has been under intensive investigation in the past few years and many photonic beam forming systems have been proposed and demonstrated Photonic beam forming network use a lightwave carrier for the electrical signals of the radiating elements of the phased array, and provides the necessary time delay and phase information for beam steering.

For airborne and space-based phased arrays operating at mm-wave frequencies (20 GHz and above), the arrays are usually two-dimensional and a large number of array elements, typically a few thousand, are used. This requires that the beam forming network be two dimensional and have a very high packing density. In addition, the beam forming network must be reversible so that it can be used for both antenna transmitting and receiving. Furthermore, the total delay achievable of the delay network must be sufficiently large so that the maximum scanning angle of the phased array is adequate. Finally, as will be shown later, the delay resolution (the minimum step of delay change) must be fine enough (much less than the wavelength of the signal) to ensure that the angular resolution of the beam scanning is sufficient.

None of the proposed photonic beam forming networks to date meet all of the above requirements. The operation frequencies of the beam forming networks based on acousto-optic modulators (E. Toughlian and H. Zmuda, "A photonic

variable RF delay line for phased array antennas," J. Lightwave Technol., vol. 8, pp. 1824–828, 1990) are limited to below 5 GHz and suffer from poor delay resolution, and therefore not adequate for mm-wave phased arrays. Path-switching time delay devices based on guided wave optics (C. T. Sullivan, S. D. Mukherjee, M. K. Hibbs-Brenner, and A. Gopinath, "Switched time-delay elements based on AlGaAs/GaAs optical wave-guide technology at 1.32 mm for optically controlled phased array antennas," SPIE Proceedings, vol. 1703, pp. 264–21, 1992) are complicated, and are characterized by high loss, high cost, poor delay resolution, and one-dimensional geometry. The free-space path-switching time delay device (N. A. Riza, "Transmit/receive time-delay beam forming optical architecture for phased array antennas," Appl. Opt., vol. 30, pp. 4594–4595, 1991) shown in FIG. 1A is a two dimensional device of high packing density, and operates at high frequency with sufficient total delay. However, as shown in FIG. 1B, the delay resolution of the device is limited by the size of the vertical dimension d of the two dimensional delay array and equals to 2 dn, where n is the refractive index of the required polarization beam splitting cube. For a d of 10 cm and a n of 1.5, the resulting delay resolution is 30 cm and is much too large for mm-wave antennas. In addition, presently the path-switched true time delay has a non-optimized design, making it bulky, expensive, and difficulty to manufacture.

Even for narrow bandwidth phased arrays where true time delay is not necessary, a compact, two dimensional, and programmable phase shifter with high phase-shift resolution is highly desirable. Such a phase shifter can reduce the size and weight, and increase the pointing accuracy of the phased array radar.

Another important application of two dimensional true time delay device is in transversal filters (B. Moslehi, K. Chau, and J. Goodman, "fiber-optic signal processors with optical gain and reconfigurable weights," Proc. 4th Biennial Department Of Defense Fiber Optics and Photonics Conf., McLean, Virginia, 1994, pp. 303–309 and D. Nortton, S. Johns, and R. Soref, "Tunable wideband microwave transversal filter using high dispersive fiber delay lines," Proc. 4th Biennial Department Of Defense Fiber Optics And Photonics Conf., McLean, Virginia, 1994, pp. 297–301). In such a filer, a microwave or mm-meter wave signal is splitted into many branches and then recombined after the signal in these branches experiences different delays. For a certain set of delays, only the signal with a right frequency will add in phase and exit the beam combining junction with minimum loss. Other frequencies will destructively interfere and suffer severe loss—a bandpass filter is formed. By changing the delay arrangements, the center frequency of the pass band will also change, creating a dynamically tunable filter often referred to as transversal filter. Studies indicate that the bandwidth of the filter is inversely proportional to the number of branches and the frequency tuning resolution is proportional to the delay resolution of the branches. Therefore, a compact, two dimensional, and programmable true time delay with high delay resolution is ideal for constructing such a filter.

Yet another application of a variable delay line with high delay resolution is in optical interferometry, and in auto- and cross-correlation measurements of optical pulses. Presently, variable delay is accomplished by the combination of various forms of mechanical translation and is fine tuned by piezo-electric transducer. Because such a delay line involves mechanical moving parts, it is generally bulky, heavy, difficult to align, and less reliable. In addition, because the piezo-electric transducer suffers from hysteresis and tem-

perature dependent drift, active control using feedback servo loop is required, resulting in a complicated system.

OBJECTS AND ADVANTAGES

Accordingly, it is an object of this invention to provide a two dimensional and variable true time delay device for phased array radar and for transversal filter applications. The device has the properties of high packing density, low loss, easy fabrication, fast delay variation, and virtually infinite bandwidth. The delay resolution of the device is sufficiently fine for accurate beam steering, and the total delay is adequately large to cover desired scanning angles. This device can be simplified to a phase-shifter beam former for phased arrays of narrow bandwidth, where true time delay is not necessary.

Another object of this invention is to provide a variable delay line which has no moving parts, no hysteresis, and no temperature dependent drift for applications in optical interferometry and optical pulse auto- and cross-correlation measurements, and in other applications where a precision variable time delay is required.

Yet another object of this invention is to provide a manufacturing method for the mass production of the variable true time delay.

Further objects and advantages of this invention will become apparent from a consideration of the ensuring description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1A** is a schematic of a prior art path-switched variable delay device.

FIG. **1B** shows that the delay resolution of the two-dimensional path-switched variable delay device is limited by the vertical dimension of the device.

FIG. **2A** shows the basic building block of an embodiment of this invention for improving the path-switched variable delay device.

FIG. **2B** shows the polarization rotator array for controlling the state of polarization in each channel.

FIG. **2C** is a cross section view of the basic building block, showing two different optical paths.

FIG. **2D** shows an injection molded building block with pockets molded for different components.

FIG. **3A** shows a ladder-structured variable delay device by stacking many basic building blocks on top of each other.

FIG. **3B** shows the binary ladder-structured variable delay device that uses fewer switching blocks.

FIG. **3C** shows a scheme to allow the ladder-structured variable delay device to operate in both directions.

FIG. **4A** is the bottom view of the variable delay device of FIG. **3**, showing that packing more channels in the horizontal direction worsens the delay resolution of the device.

FIG. **4B** shows an one dimensional ladder-structured variable delay device.

FIG. **4C** shows packing many one dimensional ladder-structured variable delay devices together creates a two dimensional device with high packing density and good delay resolution.

FIG. **5A** shows a basic unit of an index-switched variable delay device.

FIG. **5B** shows a single channel of an index-switched variable delay device.

FIG. **5C** shows a single channel of an index-switched binary variable delay device.

FIG. **6A** shows a two dimensional construction of an index-switched variable delay device.

FIG. **6B** shows a two-dimensional binary construction of an index-switched variable delay device.

FIG. **6C** shows a tunable transversal filter constructed using a two dimensional index-switched variable delay device.

FIG. **7A** shows a first implementation to allow the index-switched variable delay device to operate in both directions.

FIG. **7B** shows an alternative implementation to allow the index-switched variable delay device to operate in both directions.

FIG. **8** shows cascading an index-switched two dimensional delay device with a ladder-structured two dimensional delay device.

FIG. **9** shows a zig-zag construction of an index-switched variable delay device.

FIG. **10A** is a cross section view of the zig-zag construction of the index-switched variable delay device.

FIG. **10B** shows a 4f arrangement of the lenses used to overcome diffraction.

FIG. **10C** is another cross section view of the zig-zag construction of the index-switched variable delay device.

REFERENCE NUMERALS IN DRAWINGS

20 Optical beam **20A** Reverse direction optical beam
22 90° polarization rotator array **24L** Left Polarization Beamsplitter(PBS)
24R Right PBS **26** Corner reflector
27A Horizontal polarizer **27B** Vertical polarizer
28L Left polarization rotator **28R** Right polarization rotator
30A Horizontal Polarization **30B** Perpendicular polarization
32 Switch **34** Control signal
36 External polarization rotator **38L** Left external PBS
38R Right external PBS **40** Birefringent crystal
42 Polarization rotator **44** Electrodes
46 Laser array **48** Microwave signal
50 Photodetector array **52** Laser source
54 Collimating lens **56** Grid amplifier
58 Radiating microwave beam **60** Electrical signal combiner
62 Left laser array **64** Left collimating lens array
68L Left external polarization rotator array
68L Right external polarization rotator array
70 Left focusing lens array **72** Left photodetector array
74 Right focusing lens array **76** Right photodetector array
78 Left collimating lens array **80** Right diode laser array
82 Focusing lens **84** Photodetector
86A Upper corner reflector array **86B** Lower corner reflector array
88A Upper lens array **88B** Lower lens array
90A Upper polarization rotator array **90B** Lower polarization rotator array
92 Birefringent crystal slabs **94** Voltage
96 Microlens **98** Insulating layers

DESCRIPTION OF PREFERRED EMBODIMENTS

Referring to FIG. **2A**, the basic building block of a ladder-structured variable delay unit of this invention consists of a polarization rotator array **22**, two polarization beamsplitters (PBS) **24L** and **24R**, an optional horizontal polarizer **27A**, and an optional vertical polarizer **27B**. Polarization rotator array **22** is shown in FIG. **2B** and it may

comprises of liquid crystal polarization rotators, magneto-optical polarization rotators, or electrooptical polarization rotators. In the array, each pair of rotators **28**L and **28**R defines a signal channel and can be independently controlled. The pair should always be in the same state. For example, rotators (B,j) and (B,j') in FIG. **2**B should be "on" or "off" simultaneously, where j and j' are coordinate integers. All channels in the block share the same polarization beamsplitters and polarizers. As shown in FIG. **2**C, when a switch **32** and a control signal **34** activate a polarization rotator **28**L, a horizontal polarization state **30**A of an incoming light beam **20** is rotated 90 degrees to a perpendicular polarization **30**B, causing the beam to be reflected by polarization beamsplitters **24**L and **24**R, and going toward the output. After passing a corresponding polarization rotator **28**R at the output side, polarization state **30**B of beam **20** is rotated back to polarization state **30**A. The block is called in "reflecting state." On the other hand, when switch **32** and control signal **34** de-activate polarization rotator **28**L, polarization state **30**A of beam **20** is unchanged and the beam will pass polarization beamsplitter **24**L, going toward another basic building block. The block is called in "passing state." The optional polarizers **27**A and **27**B can be used to minimize the polarization cross-talk between the "reflecting state" and the "passing state."

To lower manufacturing cost, each building block can be injection-molded using glass, acrylic, or other types of materials. As illustrated in FIG. **2**D, slots for polarization beamsplitters **24**L and **24**R, polarizers **27**A and **27**B, and polarization rotator array **22** are pre-molded on a glass (or plastic) block. When the unit is assembled, polarization rotator array **22**, polarization beamsplitters **24**L and **24**R, and polarizers **27**A and **27**B can be simply dropped into the slots and then affixed in the slots using some epoxy that is index-matched to the building block. To further decrease the optical loss caused by the attenuation of the molding process is optical path of each channel can be made hollow. This injection molding process is especially important for mass-production of the delay units.

The ladder-structured variable delay device is constructed by stacking multiple basic building blocks on top of each other, as shown in FIG. **3**A. Whenever the beam encounters a basic block in reflecting state, it will be directed toward the output. For example, if the ith block is in reflecting state but all the blocks before it are in passing state, the total delay ΔL of the unit is

$$\Delta L=2(i-1)nh, \tag{1}$$

where n and h are the refractive index and height of the basic building block respectively. The smallest delay increment is thus.

$$\Delta l=2nh \tag{2}$$

Because the delay unit closely assembles a ladder, the structure of the delay unit is referred to as "ladder" construction. This structure is more compact than that of the conventional path switched delay shown in FIG. **1**. The ladder structure is more suited for mass production and therefore less expensive to manufacture.

To minimize the number of basic building blocks used in a ladder-structured variable delay device, the basic building blocks can be arranged in a binary fashion such that the distance between two consecutive blocks increases by a factor of 2, as shown in FIG. **3**B. Let M be the total number of the blocks used (or bits), then the maximum value of the delay generated is:

$$\Delta L_{max}=(2^0+2^1+2^2+\ldots 2^{M-1})\Delta l=(2^M-1)\Delta l \tag{3}$$

where $\Delta l \equiv 2nh$ is the smallest delay increment. By properly adjusting the polarization state of the light beam in each block, any time delay in the range from Δl to ΔL_{max} can be obtained with a resolution (or delay increment) of Δl.

The ladder-structured variable delay device can be made to operate bi-directionally by placing an external polarization beamsplitter **38**L at left end of the device, another external polarization beamsplitter **38**R at right end of the device, and an external large area polarization rotator **36** covering both the left and right ends, as shown in FIG. **3**C. For left to right operation, an optical beam **20** having a horizontal polarization **30**A enters the device from left external polarization beamsplitter **38**L. External polarization rotator **36** is de-activated to allow optical beam **20** passing through left external polarization beamsplitter **38**L and entering the delay device. On the other hand, for right to left operation, an optical beam **20**A having a perpendicular polarization **30**B enters the device by reflecting off right external polarization beamsplitter **38**R. External polarization rotator **36** is activated to rotate perpendicular polarization **30**B to horizontal polarization **30**A before entering the device. When optical beam **20**B reaches the left side of the delay device, external polarization rotator **36** automatically rotates horizontal polarization **30**A back to perpendicular polarization **30**B so that optical beam **20**A exits the delay device by reflecting off left external polarization beamsplitter **38**L.

FIG. **4**A is a bottom view of the ladder-structured delay device described above and the delay resolution is limited by the horizontal dimension d_1. To improve the delay resolution, d_1 should be reduced. The minimum d_1 equals to twice of the beam size of the light beam, at which the number of channels in the horizontal direction reduce to one, as shown in FIG. **4**B. Consequently, the 2-D delay device reduces to an 1-D delay device. However, many of such 1-D delays can be stacked together to form a high packing density of 2-D device, as shown in FIG. **4**C. Unlike the 2-D delay of FIG. **2**, the input and output channels are interlaced.

Accordingly, the ladder construction of this invention provides compactness and high packing density. The basic building block is simple and the complete unit consists of many basic building blocks that are stacked together. In addition, two or more units can be cascaded to further increase delay range. Because liquid crystals are used to control the relative delay of each channel, both control voltage and power consumption are low. By injection molding the structure of the device with glass or plastic, the fabrication cost can be greatly reduced. Because the passing states and the reflecting states have orthogonal polarizations, high delay isolation (defined as the optical power of wanted delay divided by the optical power of unwanted delay) is readily achievable with the insertion of polarizers. Finally, the optical loss of the device is low.

The delay resolution of the path switched delay described above is not fine enough for millimeter waves applications, where the delay resolution must be much less than 1 mm. The following describes an index switched variable delay device for achieving high delay resolution for mm wave and other applications where high delay resolution is required.

FIG. **5**A shows the basic unit of the index-switched variable delay device. The basic unit consists of a birefringent crystal segment **40** cut along the principal axes (X,Y,Z) of the crystal with the light beam propagating along the X axis (or Y axis). Input light beam **20** is polarized either in the Z direction or in the Y (or X) direction (the two principal directions of the crystal). The Y (or X) polarized beam

experiences a refractive index of n_o and the Z polarized beam experiences a refractive index of n_e. If the polarization of the light beam is rotated 90°, it will experience a delay difference of $\Delta l=(n_e-n_o)l$, where l is the length of the crystal segment.

A delay line can be constructed by putting many such crystal segments together in a linear array, as shown in FIG. 5B. A polarization rotator **42** is sandwiched between two neighboring segments to control the beam's polarization states. Polarization rotator **42** can be a liquid crystal, a magneto-optic, or an electro-optic element. It is evident from FIG. 5B that the time delay of the beam can easily be altered by changing beam's polarization in each segment so that the refractive index the beam experiences will change. We call this method index-switching technique. To obtain even finer delay resolution, a pair of electrodes **44** may be placed across a birefringent crystal segment for applying an electrical field and changing the refractive index of the crystal via the electro-optic (or Pockel's) effect.

To minimize the number of polarization rotators in the device, the lengths of the crystal segments increases successively by a factor of 2, as shown in FIG. 5C. The relative optical path delay Δl between the two polarization states in the smallest segment of length l (the least significant bit) is

$$\Delta l=(n_e-n_o)l. \quad (4)$$

Let M be the total number of crystal segments (or bits), then the maximum value of the delay generated is:

$$\Delta L_{max}=(2^0+2^1+2^2+\ldots 2^{M-1})\Delta l=(2^M-1)\Delta l \quad (5)$$

By properly adjusting the polarization state of the light beam in each segment **40**, any optical path delay in the range from Δl to ΔL_{max} can be obtained with a resolution (or delay increment) of Δl. Because the length of each crystal segment **40** can be tightly controlled, the accuracy of the device can be very high.

Several delay lines of the design described above can be densely packed in two dimensions to form a compact variable delay device. However, instead of cutting crystal into narrow strips, large area crystal segments **40** and polarization rotator arrays **22** (spatial light modulators) are used to construct the multiple channel delay device, as shown in FIG. **6**. Here polarization rotators in all polarization rotator arrays are aligned element by element and the size of each channel is determined by the size of the rotators. For 2 mm channel spacing, the packing density of the device is 25/cm^2. Such a channel spacing is easily attainable in practice, considering that a 1.4 mm diameter Gaussian beam with **1** Jim wavelength has a Rayleigh range of 1.54 meters.

In FIG. **6A**, the input light beams are emitted from a diode laser array **46** with each laser beam collimated by a microlens. Lasers in laser array **46** are modulated by a microwave or RF signal **48**. At the output end, each beam will be focused to a photodetector on a detector array **50** by a microlens in front of each photodetector. The photodectors will convert the optical signals into microwave or RF signals with proper delays between the channels encoded by the delay device. In FIG. **6B**, a single laser **52** is modulated by a microwave or RF signal **48**. The laser beam is then expanded by a lens **54** and passes through the delay device. At the output end, each microlens in front of each photodetector focuses the light in the corresponding channel to the corresponding photodetector on detector array **50**. The converted microwave or RF signals from all channels then incident on to a grid amplifier **56** and radiate away. The radiation angle of the resulting microwave or RF beam **58** is controlled by the relative delay relations between the delay channels.

FIG. **6C** shows a tunable transversal filter constructed by a two dimensional index switched variable delay device. In this filer, a microwave or mm-meter wave signal **48** is used to modulate a laser **52**. The laser beam is expanded and passes through a two dimensional index switched variable delay device. Different portions of the beam defined by each element of the polarization rotator arrays will experience different delays. At the output end, each microlens in front of each photodetector will focus each corresponding portion of the beam to the corresponding photodetector on detector array **50** to convert the modulated light back to the microwave or mm-wave signal. All the microwave or mm-wave signals from all the photodetectors will be summed in an electrical signal combiner **60**. For a certain set of delays, only the signal with a right frequency will add in phase and exit the beam combining junction with minimum loss. Other frequencies will destructively interfere and suffer severe loss—a bandpass filter is formed. By changing the delay arrangements, the center frequency of the pass band will also change, creating a dynamically tunable filter. Because a large number of signal channels are densely packed together, the resulting filter has a narrow bandwidth. Because the delay resolution of the index switched delay device is high, the frequency tuning resolution is also high. In addition, the fast speed of changing the delay arrangement makes tuning the filter very fast. Similar tunable filter can also be constructed with a ladder-structured optical variable delay device described earlier.

The index switched delay device can be used for both transmitting and receiving operations. As shown in FIGS. **7A** and **7B**, for the bidirectional operation, an external polarization beamsplitter (PBS) **38L** and an external polarization rotator array **68L** are placed at the left hand side of the device. Similarly, a second external PBS **38R** and a second external polarization rotator array **68R** are placed at the right hand side. Laser beams from the left hand side are polarized in the plane of the paper and passes through left PBS **38L**. On the other hand, laser beams from the right hand side are polarized perpendicular to the plane of the paper and reflect off right PBS **38R**.

In FIG. **7A**, the left laser transmitter includes a left diode laser array **62** and a left collimating lens array **64** which collimates light from each laser diode. The left receiver includes a left photodetector array **76** and a left focusing lens array **74** which focus light from each channel to a corresponding photodetector on detector array **76**. Similarly, the right laser transmitter includes a right diode laser array **80** and a left collimating lens array **78** which collimates light from each laser diode on laser array **80**. The right receiver includes a left photodetector array **72** and a left focusing lens array **70** which focus light from each channel to a corresponding photodetector on left photodetector array **72**. In FIG. **7B**, the left laser transmitter contains only a single laser **52** and a collimating lens **54**. The left side receiver consists of a single detector **84** and a focusing lens **82** that focus light from all channels to the photodetector. The laser beams transmitted from the right laser array are assumed to be incoherent.

When in the transmitting mode, left external polarization rotator array **68L** is inactive. However, right external polarization rotator array **68R** is such programmed that it always brings the polarization of light beams in each channel back to be in the plane of the paper after the delay device. This assures that light beams of all channels will pass PBS **38R** and be received by right photodetector array **76**. A left focusing lens array **74** is placed before left photodetector array **76** to focus light of each individual channel to a

corresponding detector on left photodetector array **76**. When in the receiving mode, right external polarization rotator array **68R** is inactive. However, left polarization rotator array **68L** is such programmed that it always brings the polarization of light beam in each channel back to be perpendicular to the plane of paper after the delay device. This assures that all channels will reflect off PBS **38L** and be received by a detector array **72**, as in FIG. **7A**, or a detector **84** as in FIG. **7B**.

The same concept can also be used to make phase shifters for phased array antennas with narrow bandwidth where true time delay is not necessary. For example, an 8 GHz (X-band) carrier has a wavelength of 3.75 cm. To obtain a total phase shift of 2 π for such a carrier, a total length of only 13 cm of Rutile crystal per channel is required. For a Ka band carrier of wavelength of 0.75 cm (40 GHz), only 2.6 cm Rutile crystal per channel is required.

Table I listed the birefringence of potential birefringent materials for fabricating the proposed delay lines. Note that different crystals may be used together to construct a delay line: a crystal with small birefringence can be used to make segments of small delays (less significant bits) and a crystal with large birefringence can be used to make segments of large delays (more significant bits).

TABLE I

	$n_o - n_e = \Delta l/l$	Crystal for 1 cm delay
Orpiment (AS_2S_3)	0.4	2.5 cm
Geikelite ($MgTiO_3$)	0.36	2.78 cm
Tellurite (TiO_2)	0.35	2.86 cm
Proustite	0.29	3.45 cm
Rutile (TiO_3)	0.287	3.48 cm
Ag_3AsS_3	0.28	3.57 cm
Calcite	−0.172	5.81 cm
$LiNbO_3$	−0.086	11.63 cm
Quartz	0.0091	110 cm
PM Fiber	-6×10^{-4}	~1667 cm

The maximum delay ΔL_{max} required of a beam forming network of a phased array antenna with N×N elements is

$$\Delta L_{max} = (N-1)d_{max}|\sin\theta_{max}| = \frac{(N-1)\lambda \cdot |\sin\theta_{max}|}{(1+|\sin\theta_{max}|)} \quad (6)$$

where θ_{max} is the maximum beam scanning angle, λ is the wavelength of the carrier (microwave) signal of the phased array, and $d_{max} \equiv \lambda/(1+|\sin\theta_{max}|)$ is the maximum array spacing allowed before higher order diffraction degrade the antenna gain.

To achieve an angular beam scanning resolution of $\Delta\theta$, the delay resolution or the minimum path delay between the two adjacent elements Δl is required to be

$$\Delta l = \frac{\lambda \cdot \cos\theta_{max}\Delta\theta}{(1+|\sin\theta_{max}|)} . \quad (7)$$

Table II lists the values of required maximum delay ΔL_{max} and delay resolution Δl for a phased array with λ=0.75 cm (40 GHz), N=64, and $\Delta\theta$=1°. The corresponding crystal lengths for the maximum and the minimum delays are also listed. For example, for the case of θ_{max}=30°, $LiNbO_3$ crystal of length 0.87 mm can be used to make the segment of the smallest delay of 76.5 μm and the Rutile crystal of the total length of about 55 cm can be used to make other larger delay segments that have a total delay of 15.75 cm. In the table, the number of bits M is calculated using $M=\log_2(1+\Delta L_{max}/\Delta l)$.

TABLE II

	θ_{max} = 5°	θ_{max} = 10°	θ_{max} = 30°	θ_{max} = 60°
ΔL_{max}	3.78 cm or 5.04 λ	7 cm or 9.33 λ	15.75 cm or 21 λ	21.93 cm or 29.24 λ
L_{max} (Rutile)	13.48 cm	24.4 cm	55 cm	76.4 cm
Δl	0.12 mm	0.11 mm	0.0756 mm	0.035 mm
l ($LiNbO_3$)	1.4 mm	1.3 mm	0.87 mm	0.41 mm
M No. of bits	7	8	11	12

It should be noted that Rutile has excellent optical and physical properties: it is transparent to light from 500 nm to 5 μm and its birefringence ($n_e - n_o$) remains almost unchanged from 430 nm to 4 μm. It has a density of 4.26 g/cm^3, a melting point of 2093° K, and a solubility in water less than 0.001.

To reduce the cost and to extend the delay range, the index-changing delay elements may be cascaded with a ladder structured path-switching delay device described previously, as shown in FIG. **8**. The birefringent crystal segments are used for the less significant bits of high delay resolution and the path switching concept is used for the more significant bits of large delays. This cascaded construction combines the advantages of both techniques and avoids their short comings. The total length of the crystal segments per channel is now reduced to few centimeters.

In stead of cutting crystals into many segments, the index-switching time delay unit may also be constructed using slabs of crystal, as shown in FIG. **9**. Such a unit consists of slabs of birefringent crystal **92**, a upper layer of polarization rotators **90A** (which may be individually and independently controlled), an optional lower layer polarization rotators **90B**, a upper row of corner reflectors **86A**, a lower row of corner reflectors **86B**, an optional upper lens array **88A**, and an optional lower lens array **88B**.

FIG. **10A** is a cross section view of the device. The crystal slabs are cut along the principal axes (X,Y,Z) of the crystal and light beam propagates along the X (or Y axis). The beam is polarized either in the Z direction or in the Y (or X) direction (two principal directions of the crystal). Similar to the linear construction described in FIG. **5**, here the polarization state of the light beam can also be easily switched between Y and Z direction by the 90° polarization rotators and the beam will experience n_o and n_e accordingly. Lenses **96** are used to overcome beam's diffraction and the distance between two consecutive lenses is 2f, where f is the focal length of the lenses, as shown in FIG. **10B**. In this construction the height of the crystal determines the smallest delay (delay resolution) and the total number of paths determines the maximum delay. The spacing between the polarization rotators increase successively by a factor of 2 to make the delay line binary, as in FIG. **5**. As shown in FIG. **9** and FIG. **10C**, many crystal slabs may be stacked together to construct a one dimensional delay array. Compared with the linear construction of FIG. **5**, the zig-zag construction uses less crystal. However, it is inherently one dimensional and thus has a lower packing density than that of the linear construction.

Finally, to obtain even finer delay tuning, electrodes **44** can be attached across each crystal slab to apply an electrical field **94** and change the refractive index of the crystal via the electro-optic (or Pockel's) effect of the birefringent crystals, as shown in FIG. **9** and FIG. **10C**. The two electrodes on each face of crystal slab **92** can be separated by an insulation layer **98**.

In summary, the index switched photonic variable delay device has the properties of high packing density, low loss, easy fabrication, and virtually infinite bandwidth. The device is inherently two dimensional and has a packing density exceeding 25 lines/cm^2. The delay resolution of the device can be much less than a femtosecond (one micron in space) and its total delay exceeds 1 nanosecond. The delay accuracy achievable is high, and is only limited by the length accuracy of each crystal segment. The device can also be digitally programmed with low switching power (microwatts per switch or per bit). Such a device is ideal for a beam forming network of a phased array operating at Ka band (~40 GHz) and above frequencies and for millimeter wave transversal filters. In addition, the delay is reversible so that the same delay device can be used for both antenna transmitting and receiving. Finally, this index-switched variable delay device can be cascaded with a ladder-structured variable device to form a new device which combines the advantages of the two individual devices.

Although the description above contains many specificaties, these should not be construed as limiting the scope of the invention but as merely providing illustrations of some of the presently preferred embodiments of this invention.

Thus, the scope of the invention should be determined by the appended claims and their legal equivalents, rather than by the examples given.

What is claimed is:

1. A ladder-structured multi-channel optical device for independently varying a path length of an optical beam of each channel, comprising:

A first polarization beamsplitter and a second polarization beamsplitter being arranged as a polarization sensitive corner reflector operable to pass the optical beam of a first polarization state and reflect the optical beam of an orthogonal polarization state;

a polarization rotator array containing multiple polarization rotators each independently operable to rotate the first polarization state to the orthogonal polarization state when being activated and leave the first polarization state unaffected when being de-activated;

said polarization rotator array being placed parallel to a hypotenuse of the polarization sensitive corner reflector to form a basic unit with the corner reflector;

multiple basic units being stacked on top of each other with all the polarization rotator arrays being parallel to one another and aligned;

each polarization rotator in a basic unit being controlled either for the optical beam to pass to an upper level unit or to be reflected towards a lower level unit, thereby altering the path length of the optical beam exiting the device.

2. The ladder-structured variable delay device of claim 1 wherein the distance between two adjacent basic units increases successively by a factor of 2.

3. A ladder-structured multi-channel optical device of claim 1 wherein each rotator in the polarization rotator array of each basic unit has a conjugate rotator symmetrically located about a center plane of the corner reflector to rotate the orthogonal polarization state of the reflected optical beam back to the first polarization state before the beam going to a lower level basic unit.

4. The ladder-structured variable delay device of claim 3 wherein said polarization rotator array has two elements in a horizontal direction so that each rotator at a left portion of the array is adjacent to its conjugate rotator at a right portion, whereby creating a one dimensional multi-channel variable delay device with an improved delay resolution.

5. The ladder-structured variable delay device of claim 4 wherein multiple one dimensional devices are packed side by side to form a two dimensional device with interlaced input and output ports.

6. The ladder-structured variable delay device of claim 1 wherein said polarization rotator array is fabricated with a material selected from the group consisting of liquid crystals, magneto-optic materials, and electro-optic crystals.

7. The ladder-structured multi-channel variable delay device of claim 1 further comprising:

a photodetector array having multiple photodetectors each operable to receive a modulated optical beam from a corresponding channel of the variable delay device and convert it into an electrical signal; an electrical signal combiner having multiple input ports to receive multiple electrical signals and operable to combine the received electrical signals; each input port of the electrical signal combiner being connected to an output port of a corresponding photodetector, whereby creating a dynamically tunable RF filter.

8. The ladder-structured variable delay device of claim 1 further comprising:

A left external polarization beamsplitter, followed by a left external polarization rotator array, being placed at a left side of the variable delay device; a right external polarization beamsplitter, followed by a right external polarization rotator array, being placed at a right side of the variable delay device.

9. The ladder-structured variable delay device of claim 1 wherein each basic unit further comprising:

a first polarizer being placed between said first and said second polarization beamsplitters for blocking the optical beam of the first polarization state, and/or a second polarizer being placed parallel to the hypotenuse of the corner reflector for blocking the optical beam of the orthogonal polarization state.

10. The ladder-structured variable delay device of claim 9 wherein a body of each basic unit is injection molded with pockets for holding said polarization rotator arrays, said first and second polarization beamsplitters, and said first and second polarizers.

11. The ladder-structured variable delay device of claim 1 wherein a different multi-channel variable delay device is cascaded with the ladder-structured variable delay device, with each channel of the device aligned with each channel of the different device to form a cascaded multi-channel variable delay device.

12. The ladder-structured variable delay device of claim 11 wherein the different variable delay device is an index switched variable delay device constructed with birefringent crystals.

13. A ladder-structured optical device for varying a path length of an optical beam, comprising:

A basic unit comprising a first polarization beamsplitter, a second polarization beamsplitter, and a polarization rotator; the first polarization beamsplitter and the second polarization beamsplitter being arranged as a polarization sensitive corner reflector operable to pass the optical beam of a first polarization state and reflect the optical beam of an orthogonal polarization state; the polarization rotator being placed parallel to a hypotenuse of the corner reflector and operable to rotate the first polarization state to the orthogonal polarization state with an activation signal; multiple basic units being stacked on top of each other with all the polarization rotators being parallel to one another.

14. The ladder-structured variable delay device of claim 13 wherein the polarization rotator in each basic unit is an array consisting of more than one independently operable elements.

15. The ladder-structured variable delay device of claim 14 wherein multiple similar devices are packed side by side to form a different variable delay device with increased channels.

16. The ladder-structured variable delay device of claim 13 wherein each basic unit further comprising:

a first polarizer being placed between said first and said second polarization beamsplitters for blocking the optical beam of the first polarization state and/or a second polarizer being placed parallel to the hypotenuse of the corner reflector for blocking the optical beam of the orthogonal polarization state.

17. The ladder-structured variable delay device of claim 16 wherein a body of each basic unit is injection molded with pockets for said polarization rotator, said first and said second polarization beamsplitters, and said first and second polarizers.

18. The ladder-structured variable delay device of claim 13 further comprising:

A left external polarization beamsplitter, followed by a left external polarization rotator, being placed at a left side of the variable delay device; a right external polarization beamsplitter, followed by a right external polarization rotator, being placed at a right side of the variable delay device.

19. The ladder-structured variable delay device of claim 13 being cascaded with a different variable delay device.

20. A method of varying an optical path length of an optical beam by switching the optical beam into different paths, comprising the steps of:

forming a polarization sensitive corner reflector operable to pass the optical beam of a first polarization state and reflect the optical beam of an orthogonal polarization state with a first polarization beamsplitter and a second polarization beamsplitter;

selecting a polarization rotator operable to change the first polarization state to the orthogonal polarization state when being activated and leave the first polarization state unaffected when being de-activated;

placing the polarization rotator parallel to a hypotenuse of the polarization sensitive corner reflector to form a basic unit with the corner reflector;

stacking multiple basic units on top of each other with all polarization rotators being parallel to one another and aligned;

placing a stack of the basic units in the path of the optical beam of the first polarization state;

activating the polarization rotator of a first basic unit to cause the optical beam to be reflected by the corner reflector of the first basic unit towards output, resulting in a smallest optical path length;

de-activating the polarization rotator of the first unit and activating the polarization rotator of a second basic unit to allow the optical beam to pass the second basic unit and be reflected by the corner reflector of the second unit towards output, resulting in a second optical path length;

activating the polarization rotator of a nth unit while de-activating the polarization rotators of all units before it to cause the optical beam to be reflected by the corner reflector of the nth unit towards output, resulting in a nth optical path length;

activating and de-activating the polarization rotator of each unit selectively to obtain a desired optical path length.

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